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Advancements in hybrid nanofluids for diesel engine thermal management: a comparative review

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Hybrid nanofluids show considerable promise for improving thermal management in diesel engines – outperforming both single-nanoparticle fluids and standard coolants. When it comes to performance, we rigorously evaluated multiple hybrid formulations against four key metrics: thermal conductivity, viscosity, long-term stability, and corrosion resistance. Blending specific nanoparticle types, namely alumina (Al_2O_3), silica (SiO_2), and titania (TiO_2), with carefully chosen surfactant agents. This combination directly boosted how effectively these fluids transfer thermal energy. The research demonstrates that hybrid nanofluids substantially boost thermal conductivity, increasing it by 30% to 50% compared to conventional coolants. In particular, the Al_2O_3-SiO_2-TiO_2 combination showed exceptional effectiveness, surpassing other nanofluid mixtures by roughly 20–30%. Surfactants significantly enhanced the dispersion of nanoparticles, reduced their aggregation, and decreased viscosity by around 10–15%, which subsequently reduced the energy required for pumping. These advancements increased the durability and reliability of hybrid nanofluids, thereby broadening their potential applications. The study emphasized the importance of surfactants in maintaining effective nanoparticle suspension and preventing sedimentation, ensuring sustained stability. Among all the compounds analyzed, the surfactant-modified Al_2O_3-SiO_2-TiO_2 nanocomposite blend showed superior outcomes, striking a balance between enhanced thermal conductivity, stability, and controllable viscosity. Hybrid nanofluids present a promising method for improving diesel engine cooling; however, significant obstacles such as cost, scalability, and durability remain. This study tackles these barriers and contributes valuable perspectives for advancing thermal management technologies. The paper amalgamates experimental and theoretical findings from 82 peer-reviewed studies, providing a comparative analysis without introducing new experimental data.

Keywords: *hybrid nanofluids, diesel engine cooling, thermal management, heat transfer, stability, viscosity reduction*

1. Introduction

Efficient thermal management is at the heart of achieving diesel engine performance, reliability, and durability. Excessive heat production during the operation of engines could lead to thermal stress, reduced fuel efficiency, increased emissions, and increased wear of sensitive components. Excessive build-up of heat, if not properly released, could lead to a compromise in engine performance, resulting in early failure and increased maintenance costs. To mitigate these challenges, cooling systems have been used to maintain engine temperature and achieve optimum operation [49]. Diesel engines have conventionally relied on conventional coolant systems that utilize a mix of water and ethylene glycol as a working fluid. Such coolants utilize convective heat transfer as a predominant mechanism, dissipating excess heat generated in the engine and conveying it through radiators and cooling passages. These cooling fluids have been predominant due to ease of use and compatibility with common engine components, as well as affordability and ease of implementation. However, as engines have been developed to accommodate increased power output and stringent emissions regulations, weaknesses of conventional coolants have been revealed, and superior thermal management technologies have been sought [23, 45].

One of the serious drawbacks of traditional coolant systems is that they have a comparatively low thermal conductivity that barely enables them to reject heat under high-load operation effectively [3, 41]. Although water is a very popular base fluid in cooling systems due to its excellent heat capacity, it is still found wanting when it comes to thermal conductivity and thus compromises the overall performance of a cooling system. Ethylene glycol, often combined with water to inhibit freezing and corrosion, intensifies this drawback by reducing the coolant's thermal conductivity. Moreover, conventional coolants experience more significant degradation over time as a result of thermal cycling, chemical instability, and exposure to contaminants [8]. This degradation results in reduced heat transfer efficiency, increased likelihood of corrosion, and deposit formation within the cooling system, which can hinder flow channels and make cooling operations more challenging. These drawbacks are particularly prominent in high-performance and heavy-duty diesel engines, where the increased thermal demands necessitate more efficient heat dissipation techniques to avoid overheating and ensure long-term reliability [37, 38].

Nanofluids are next-generation heat transfer fluids consisting of nanoparticles in conventional base fluids such as water, ethylene glycol (EG), or oil. The thermal conductivity, heat transfer coefficient, and fluid stability are improved significantly by these nanoparticles, and thus, nanofluids are quite suitable in engine cooling systems. Among numerous different formulations, surfactant-stabilized metal oxide or hybrid particle-based water-based nanofluids are the most effective in engine coolant applications [79]**.** According to the kind of nanoparticle used, nanofluids are single nanofluids (a single type of nanoparticle) or hybrid nanofluids (two or multiple different nanoparticles), and are divided according to these characteristics. In both cases, suspension stability is a leading aspect that determines them due to the tendency of nanoparticles to agglomerate as a result of van der Waals forces. In order to address this, surfactants are often utilized as they go a long way towards enhancing dispersibility, reducing sedimentation, and increasing the heat transfer coefficient in nanofluids [40].

The exploration of nanofluids as a substitute for conventional coolants has been a focal point for researchers aiming to overcome current obstacles. Nanofluids are meticulously crafted mixtures of nanoparticles suspended in a base fluid, intended to enhance the heat transfer capabilities of standard cooling systems. Nonetheless, the practical application of single-component nanofluids is often restricted by certain limitations, inhibiting their extensive adoption in diesel engines. Specifically, these constraints restrict the integration of single-component nanofluids into diesel engine systems. The inclusion of thermally conductive nanoparticles, such as aluminum oxide (Al_2O_3), copper oxide (CuO), silicon dioxide (SiO_2), and titanium dioxide (TiO_2), has shown substantial improvement in the heat transfer capabilities of base fluids by enhancing thermal conductivity and convection heat transfer rates. Nevertheless, nanofluids created through conventional methods often suffer from instability, resulting in rapid sedimentation that diminishes their effectiveness in heat transfer. Nanoparticles, due to their small size, interact more effectively with fluids, thereby reducing thermal resistance and improving the efficiency of heat dissipation [34, 66]. At present, a significant hurdle in the application of nanofluid technology is resolving issues such as particle sedimentation, heightened viscosity, extended instability, and potential material incompatibility. Tackling these essential challenges is vital for the adoption of nanofluids as viable alternatives to traditional cooling fluids in practical scenarios.

Hybrid nanofluids have emerged as a new approach to solving the single-component nanofluid problems inherent in diesel engine heat transfer. While single-component nanofluids do not perform all of these functions sufficiently, hybrid nanofluids have been found to use a base fluid with two or more types of nanoparticle-allowing researchers to make full use complementarity between different materials and thus enhance thermal performance [30]. Hybrid nanofluids with different nanoparticle compositions can have better thermal conductivity, dispersant additional stability, and the compatibility of viscosity and composite technology with bombarding particles. For example, use a combination of metallic and metallic oxide nanoparticles; this not only increases the heat transfer of the original fluid but also reduces aggregate sediment at the same time. Furthermore, by using surfactant modifiers and new dispersion technology, the long-term stability of hybrid nanofluids has gone up, making them more feasible for practical cooling applications [5, 82]. As a result, hybrid nanofluids boast high potential in surpassing traditional coolants. They also effectively address what single-component nanofluids lack.

With the increasing complexity of modern diesel engines today, coupled with the ever-growing need for energy efficiency and environmental protection, advanced cooling solutions have been thrown into sharp relief. As engine power output continues to climb, traditional systems are struggling to cope with ever-increasing heat loads, demanding more innovative and effective methods for thermal management [11, 33]. Using water as the base fluid, hybrid nanofluids have demonstrated significant potential, providing an efficient approach to boost convective heat transfer while remaining stable and compatible with the components of current cooling systems. The integration of hybrid nanofluids into diesel engine cooling systems has the potential to reduce engine operating temperatures, improve fuel efficiency, minimize wear and tear, and lower emissions, making them an attractive research focus for both academia and industry [6].

Despite their significantly enhanced thermal conductivity, ionic liquids continue to present a concern due to their corrosive nature. Some ionic liquids have been found to accelerate corrosion in aluminum and copper components; corrosion inhibitors or protective coatings must be used to avoid this situation entirely. For example, [56] NG SAIC has shown that in hybrid nanofluids containing ionic liquids, a further 58 certainly can reduce the corrosion speed by 40%.

Although hybrid nanofluids appear quite promising, their application in diesel engines remains restricted. The main challenges involve achieving cost-effectiveness, scalability, and reliable performance under diverse conditions. While extensive research has been done on nanofluids for thermal management, comprehensive comparative analyses of different hybrid nanofluid formulations specifically for cooling diesel engines are lacking. This review aims to bridge this gap by thoroughly evaluating different hybrid nanofluids, focusing on crucial performance metrics such as thermal conductivity, viscosity, dispersion stability, corrosion resistance, and cost-effectiveness. This review combines insights from previous research and theoretical perspectives to offer a thorough evaluation of the practicality and effectiveness of hybrid nanofluid cooling systems. It places special emphasis on the crucial role of surfactants in optimizing nanoparticle dispersion and enhancing thermophysical properties. Additionally, it scrutinizes the potential for large-scale implementation, cost limitations, and regulatory hurdles. The primary aim is to aid the future design of thermal management strategies by pinpointing the most efficient hybrid nanofluid formulations and resolving barriers to their application, thus fostering the development of more efficient, durable, and eco-friendly cooling systems for diesel engines. It should be noted that this review relies exclusively on previously published literature, unless indicated differently. All figures, tables, and quantitative data are taken from the literature with appropriate references, and any original visual content is specified. This work does not include any new experimental investigations. Primarily synthesizing existing research, this review also identifies key research gaps, particularly regarding long-term operational stability and large-scale applications, and proposes directions for future research in this dynamic field.

2. Nanofluids as an emerging solution

In recent years, nanofluids have emerged as a revolutionary innovation in thermal management systems, particularly for cooling engines. By incorporating nanoparticles into typical base fluids such as water, ethylene glycol, or oil, these nanofluids offer considerably enhanced heat transfer properties due to the nanoparticles' high thermal conductivity [15]. This enhanced thermal efficiency leads to better temperature regulation, decreased thermal resistance, and improved cooling performance. Unlike traditional cooling fluids, nanofluids deliver greater stability, lower viscosity, and better convective heat transfer, making them ideal for high-performance engines, power plants, and a variety of industrial applications [9].

Nanofluids play a crucial role in boosting energy efficiency and promoting environmental sustainability. They manage this by enabling more efficient heat dispersal, reducing the overheating risk, and thereby extending the engine's operational life. Incorporating nanoparticles like aluminum oxide (Al_2O_3), copper oxide (CuO), and carbon-based compounds such as graphene enhances the coolant's thermal and flow properties. Despite persistent challenges related to nanoparticle dispersion, stability, and potential corrosion, ongoing advancements in nanotechnology are persistently addressing these concerns [28, 29]. As a result, nanofluids are being increasingly acknowledged as transformative components set to innovate cooling solutions in automotive and industrial contexts.

3. Composition of single and hybrid nanofluids with surfactants

3.1. Single nanoparticle-based nanofluids

To improve heat transfer characteristics, nanofluids consisting of a single type of nanoparticle are formulated by uniformly distributing these nanoparticles within a base fluid. Diverse research investigations have explored the efficacy of various nanoparticles, including metal oxides, pure metals, and carbon-based materials, for cooling applications (see Fig. 1). Nanofluids that combine metal oxides like alumina oxide-water (Al_2O_3-water) and copper oxide-water (CuO-water) exhibit significant enhancements in thermal conductivity, stability, and material compatibility, making them highly valuable for cooling engines [56]. Metal oxide nanoparticles including aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), zinc oxide (ZnO), copper oxide (CuO), and iron oxide (Fe_3O_4) are widely utilized due to their remarkable stability, effective dispersion in water, and moderate rise in thermal conductivity. In contrast, pure metal nanoparticles like copper (Cu), silver (Ag), and gold (Au) offer outstanding thermal conductivity but tend to oxidize, which requires the application of surface treatments or surfactants to ensure stable dispersions. On the other hand, carbon-based nanoparticles, including carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), and fullerenes, are noted for their outstanding thermal attributes due to high surface area and exceptional phonon transport, though their dispersion in polar solvents such as water presents a significant challenge [22, 24].

In single-component nanofluids, the typical nanoparticle concentration ranges from 0.1% to 5% by volume. Increasing this concentration can adversely affect viscosity, potentially increasing the need for pumping power and reducing coolant circulation efficiency. Thus, selecting nanoparticles demands an evaluation of the specific application requirements, the desired thermal performance, and their compatibility with existing cooling systems.

3.2. Hybrid nanoparticle-based nanofluids

Hybrid nanofluids utilize a combination of two or more distinct nanoparticles to synergistically improve thermal conductivity, stability, and viscosity management, thereby addressing the limitations of nanofluids based on a single type of nanoparticle [12]. These constraints encompass challenges such as sedimentation, heightened viscosity, and only moderate improvements in heat transfer. Commonly studied hybrid nanoparticle types include metal-metal oxide combinations (like Cu-Al_2O_3, Ag-TiO_2, CuO-ZnO), metal-

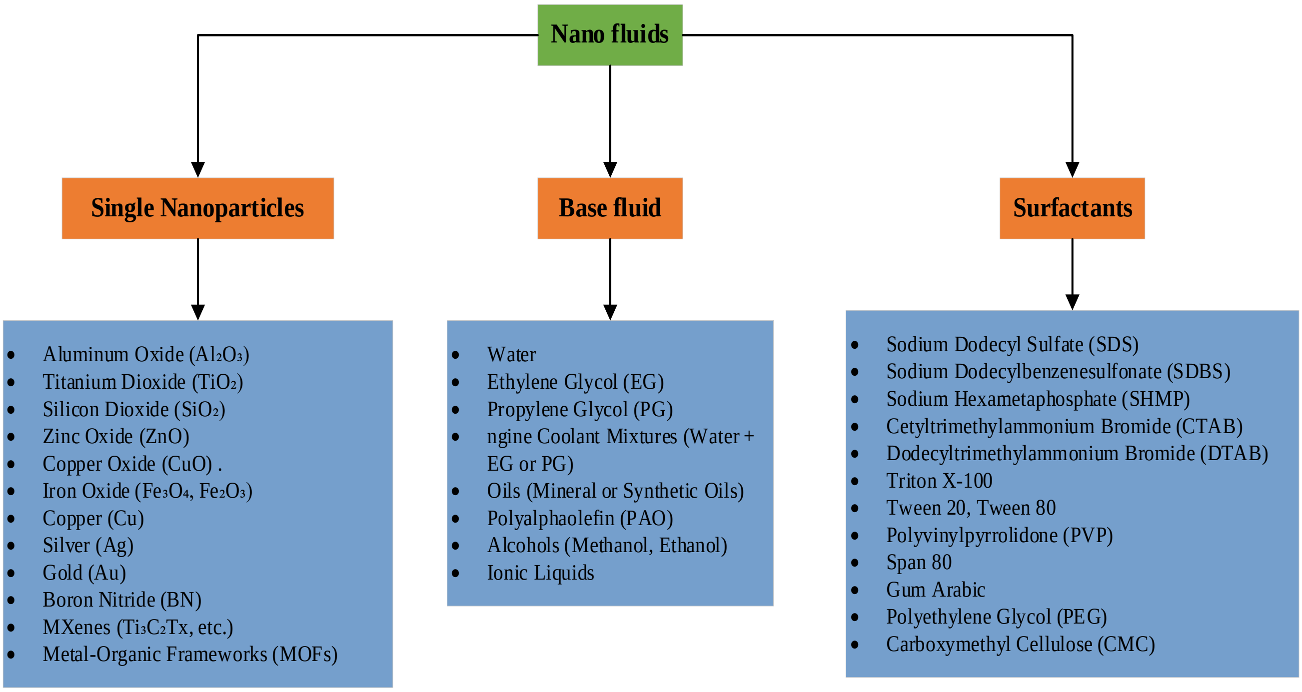

Fig. 1. Single nanoparticle-based nanofluids

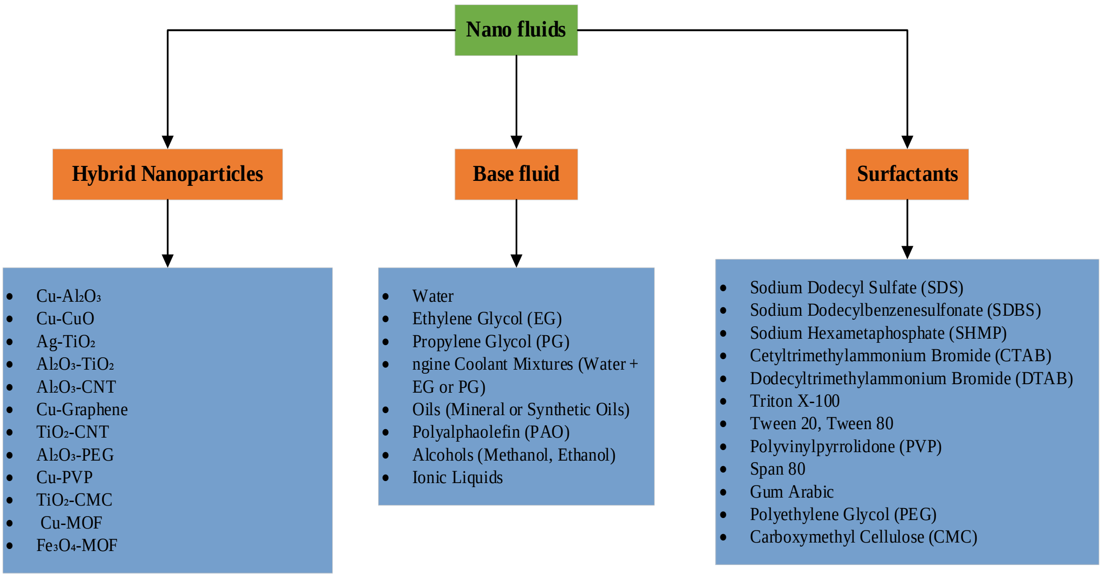

Fig. 2. Hybrid nanoparticle-based nanofluids. Studies have demonstrated that hybrid nanofluids exhibit higher thermal conductivity, improved stability, and reduced viscosity compared to single nanofluids. The enhanced properties result from the combination of high-conductivity materials with nanoparticles that provide improved dispersion and stability in the base fluid. However, the formulation of hybrid nanofluids requires precise control over nanoparticle ratios, dispersion techniques, and long-term stability considerations

carbon mixtures (such as Al_2O_3-CNT, Cu-Graphene, TiO_2-GNP), and metal-polymer blends (such as Al_2O_3-PEG, Cu-PVP) (Fig. 2) [18, 19]. Among these, hybrid nanofluids such as Al_2O_3-CuO and TiO_2-CNT show outstanding potential for engine cooling applications, thanks to their superior thermal conductivity, enhanced stability, and optimized viscosity [58]. Choosing nanoparticles suitable for hybrid nanofluids involves a careful assessment of thermal efficiency, fluid stability, and viscosity management.

3.3. Role of surfactants in nanofluid stability

One of the main challenges in manufacturing nanofluids is ensuring that nanoparticles remain uniformly distributed in the base liquid for prolonged durations. Nanoparticles often have a tendency to cluster because of attractive van der Waals forces, which can result in the formation of sediment, potential obstructions, and reduced thermal efficiency [42]. To address these challenges, surfactants – also known as dispersants or stabilizers – are used to alter the surface properties of nanoparticles, thus enhancing their interaction with the base fluid. Nonionic surfactants like polyvinylpyrrolidone (PVP) and Triton X-100 are especially effective in engine coolant applications. Notable characteristics include superior dispersion abilities, robust chemical resistance, and a minimal impact on the fluid's viscosity [71].

Surfactants can be grouped into four categories according to their charge: anionic, cationic, nonionic, and polymeric. Anionic surfactants, like sodium dodecyl sulfate (SDS), sodium dodecylbenzene sulfonate (SDBS), and sodium hexametaphosphate (SHMP), are notably efficient at stabilizing metal oxide nanoparticles such as Al_2O_3, TiO_2, and CuO in water-based solutions. In contrast, cationic surfactants like cetyltrimethylammonium bromide (CTAB) and dodecyl trimethylammonium bromide (DTAB) are used to stabilize carbon-based and metallic nanoparticles in nonpolar solvents. Nonionic surfactants like Triton X-100, Tween 20, Tween 80, PVP, and Span 80 are preferred because of their broad compatibility and limited interaction with coolant additives [17]. Moreover, polymeric dispersants like polyethylene glycol (PEG), carboxymethyl cellulose (CMC), and gum arabic significantly improve the long-term stability of nanoparticles by effectively inhibiting their agglomeration and sedimentation [26, 31].

To effectively stabilize nanoparticles while preventing significant fluid viscosity increases or thermal conductivity decreases, it is vital to maintain optimal surfactant concentrations, preferably ranging from 0.1 to 2% by weight. However, an excess of surfactants can lead to foaming, increased flow resistance, and compatibility issues with cooling system materials. Therefore, careful selection and adjustment of surfactant types and concentrations are necessary to guarantee the performance and reliability of nanofluids.

3.4. Optimization of nanofluid composition

The effectiveness of nanofluids is significantly influenced by the precise mix of nanoparticles, base fluid, and surfactants [32, 76]. To create efficient nanofluids suitable for engine cooling, it is crucial to enhance thermal conductivity, preserve stability, control viscosity, and verify compatibility with cooling systems. Research indicates that water-based nanofluids containing Al_2O_3, CuO, or hybrid combinations like Al_2O_3-CuO, stabilized with non-ionic surfactants such as PVP, are particularly well-suited for automotive engine use. These formulations exhibit excellent heat transfer performance, maintain stability over time, and have a negligible impact on viscosity [73]. Materials with high thermal conductivity, like copper (Cu), silver (Ag), and graphene, can greatly boost heat transfer but often require specific stabilization methods to prevent oxidation or clumping. The selection of suitable surfactants is essential for ensuring uniform dispersion and lasting stability. On the other hand, a high nanoparticle concentration or the choice of inappropriate surfactants may result in an increase in viscosity, negatively impacting coolant flow and heat transfer effectiveness [59].

Recent studies indicate that well-optimized hybrid nanofluids, when combined with the right surfactants, can enhance thermal conductivity by 30% to 50% over traditional coolants, making them very appealing for modern engine cooling systems [39, 45]. Ongoing research is investigating functionalized nanoparticles, new dispersion techniques, and innovative surfactant formulations, which are anticipated to further advance nanofluid technology, providing effective and sustainable options for future automotive and industrial cooling applications.

4. Performance metrics and evaluation criteria

4.1. Effects of single nanofluid usage in engine cooling

The effectiveness of using both single and hybrid nanofluids to cool diesel engines is contingent on factors such as thermal conductivity, viscosity, stability, and compatibility with materials. Viscosity is crucial for defining the required pumping power and the flow characteristics of the nanofluids. While higher viscosity formulations might improve thermal conductivity, they typically lead to greater energy consumption. Hence, it is essential to maintain a balanced relationship among these factors. This review assesses nanofluid formulations according to five primary criteria: (1) enhancements in thermal conductivity, (2) impact on viscosity, (3) long-term stability, (4) potential for corrosion, and (5) economic feasibility. The improvement in thermal conductivity significantly boosts heat dissipation, resulting in a 30% to 50% increase over traditional coolants [60]. Hybrid nanofluids often outperform single-component formulations by striking an ideal balance between thermal efficiency and stability. Despite the advantages of higher thermal conductivity, controlling viscosity is essential to prevent unnecessary energy consumption. Increased viscosity demands more pumping power, which could undermine the advantages of enhanced thermal conductivity.

Optimal nanoparticle concentrations, generally between 0.1% and 1%, have been found to effectively balance heat transfer performance and fluid flow efficiency [73]. Moreover, stability is essential to avoid issues such as sedimentation and particle clumping. Nanoparticles like SiO_2 and TiO_2 show outstanding dispersion characteristics, and employing surfactants can further enhance uniformity. Instability can cause system blockages and inconsistent heat transfer, reducing cooling efficiency. The compatibility of materials is critical because nanoparticles such as CuO can significantly increase corrosion rates [50, 78]. Furthermore, nanoparticles such as CuO and Fe_3O_4 may exhibit corrosive behaviors, which could impact the long-term durability of engine components. While surfactants like sodium dodecyl sulfate (SDS) have the potential to form protective coatings that minimize corrosion, additional research is necessary to understand their prolonged effects on metals like copper and aluminum. Future investigations should implement standardized corrosion testing protocols utilizing copper and silver plates. Non-corrosive options like Al_2O_3 and SiO_2, together with protective coatings and passivation strategies, can reduce corrosion risks and maintain system integrity. Ensuring chemical stability is crucial for the ongoing use of both single and hybrid nanofluids in diesel engines.

Considerable attention has been focused on the use of various nanofluids in engine cooling systems, as they can enhance thermal management and increase engine performance. Figure 3 illustrates that integrating nanofluids into these systems can improve heat transfer, lower operational temperatures, and offer enhanced thermal stability. However, the efficacy of nanofluids is heavily contingent on the nanoparticle type utilized, as presented in Table 1. Nanoparticles like Al_2O_3 and TiO_2 are prized for their outstanding stability and resistance to corrosion, making them ideal for prolonged use in cooling systems [56]. Nanoparticles like CuO and Fe_3O_4 demonstrate impressive thermal conductivity, yet they also pose challenges such as increased viscosity and a greater risk of corrosion, which could damage engine components. On the other hand, carbon-based nanoparticles, including Multi-Walled Carbon Nanotubes (MWCNTs) and Graphene Nanoplatelets, are well-noted for their excellent thermal conductivity and have the potential to significantly boost cooling efficiency.

Despite this, practical application is hindered by challenges such as increased viscosity, instability, high costs, and the tendency of particles to agglomerate and settle, causing blockages and reducing cooling efficiency [2, 13, 46]. These challenges highlight the importance of meticulously choosing nanoparticles to meet distinct cooling demands. In engine cooling systems, economic considerations greatly influence the choice of nanoparticles. SiO_2 and ZnO nanoparticles present a cost-efficient blend of thermal performance, stability, and corrosion resistance, making them suitable for budget-conscious scenarios requiring dependable solutions.

Conversely, the financial burden and technical challenges associated with MWCNTs and Graphene Nanoplatelets limit their application in extensive industrial environments [13, 27]. Achieving an optimal equilibrium between cost and performance is essential for the advancement of effective nanofluid-based cooling systems.

Although promising, single nanofluids grapple with major adoption barriers due to a crucial compromise between thermal conductivity and viscosity. High viscosity linked with nanoparticles like MWCNTs and Graphene Nanoplatelets demands greater pumping power, which negatively affects fluid dynamics and overall system performance [16]. Stability presents another major issue, as nanoparticles such as CuO and Fe_3O_4 are prone to agglomeration and sedimentation, reducing the system's effectiveness over an extended period. Although Al_2O_3 and TiO_2 nanoparticles offer improved stability, their thermal conductivity is insufficient for optimal cooling performance. Moreover, addressing nanoparticle-induced corrosion requires either using corrosion inhibitors or opting for alternative nanoparticle materials [75]. Ensuring the longevity and functional effectiveness of nanofluid cooling systems necessitates systematic solutions to stability and corrosion problems. If not addressed, these challenges can compromise thermal efficiency and the longevity of engine components. In addition to these technical concerns, economic factors also pose a barrier to broad implementation. As detailed in Table 1, the steep price of advanced nanoparticles – like MWCNTs and graphene nano-platelets – makes them untenable for widespread industrial deployment, especially in sectors sensitive to costs [1, 68]. High expenses also hinder the adoption of single nanofluids. The prohibitive costs of carbon-based nanoparticles, coupled with the moderate performance of cheaper alternatives like SiO_2 and ZnO, highlight the need for cost-effective solutions. Future studies should focus on improving the techniques for synthesizing and manufacturing nanoparticles to increase efficiency and maintain cost-effectiveness [7, 74].

While single-component nanofluids offer substantial promise for improving engine cooling, their real-world application is currently limited due to issues such as elevated viscosity, long-term instability, corrosion hazards, and costly materials. To achieve the ideal balance between thermal efficiency and system integration, it is essential to pursue novel approaches like developing hybrid nanofluids or implementing surface modification techniques. Future research should prioritize evaluating the longevity and effectiveness of nanofluids in real-world conditions to maintain reliability and material integrity. In Figure 1, the illustration and Table 1, the summary highlights the importance of carefully choosing and combining nanoparticles to maintain a balance between improved thermal capabilities and usability. Addressing these technical and economic hurdles is vital to fully unlocking the potential of nanofluid technology for modern engine cooling systems.

Table 1. Summary of single nanofluid effects (original synthesis based on data from [49, 43, 34, 66])

Nanoparticle	Thermal conductivity (W/m·K)	Viscosity effect	Stability	Corrosion effect	Density (kg/m³)	Cost	Overall rank	Author reference
Al_2O_3 (aluminum oxide)	✓ low (~30)	✓✓ Low	✓✓✓ Excellent	✓✓✓ Low	3970	✓✓✓ Cheap	☆☆☆ (3.6/5)	[43, 49]
CuO (copper oxide)	✓✓✓ High (~70)	✗ High	✓✓ Moderate	✗ Can corrode	6310	✗ Expensive	☆☆☆ (3.1/5)	[34, 66, 82]
TiO_2 (titanium dioxide)	✓ Moderate (~11)	✓✓ Low	✓✓✓ Excellent	✓✓✓ Very Low	4230	✓✓ Cheap	☆☆☆ (3.5/5)	[31, 60]
SiO_2 (silicon dioxide)	✓ Moderate (~1.4)	✓ Low	✓✓✓ Excellent	✓✓ Low	2650	✓✓✓ Very Cheap	☆☆☆ (3.7/5)	[36, 39, 57]
ZnO (zinc oxide)	✓✓ Moderate (~23)	✓✓ Low	✓✓✓ Good	✓✓ Low	5610	✓✓ Affordable	☆☆☆ (3.3/5)	[3, 72]
Fe_3O_4 (magnetite iron oxide)	✓✓ High (~80)	✗ High	✓ Moderate	✗ Corrosive	5180	✗ Expensive	☆☆☆ (3.1/5)	[35, 67]
MWCNT (multi-walled carbon nanotubes)	✓✓✓ Very High (~3000)	✗✗ Very High	✗ Poor	✓✓ Low	~1400	✗✗ Very Expensive	☆☆☆ (3.9/5)	[12, 13, 67]
Graphene nano-platelets	✓✓✓ Very High (~5000)	✗ High	✓✓ Moderate	✓ Low	~2200	✗ Expensive	☆☆☆☆ (4/5)	[9, 64]

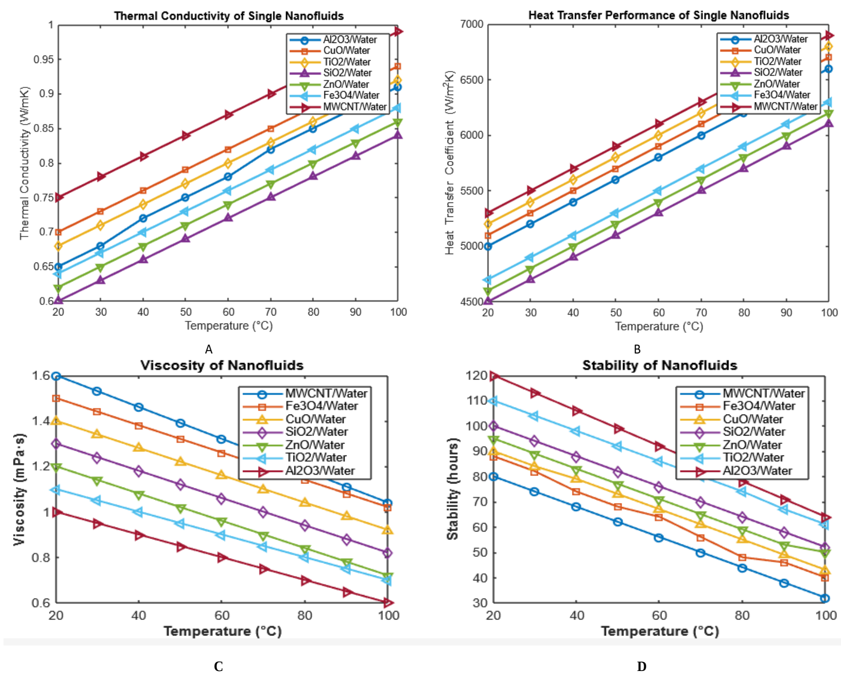

Fig. 3. Effects of single nanofluid usage (adapted with permission from [49]; experimental data from [43]

4.2. Effects of hybrid nanofluid usage in engine cooling

Hybrid nanofluids have recently captured attention for their exceptional ability to improve thermal management and enhance engine cooling system efficiency. Figure 4 demonstrates that these nanofluids possess superior heat transfer capabilities compared to conventional coolants, resulting in reduced operating temperatures and enhanced thermal stability [44, 48]. Table 2 illustrates that the effectiveness of these fluids greatly depends on the specific nanoparticle combinations used. As a result, selecting suitable hybrid formulations is crucial for improving cooling performance while maintaining a balance between efficiency, stability, and cost-effectiveness.

Hybrid nanofluids, specifically combinations of metals and metal oxides like Cu-Al_2O_3/water and Cu-TiO_2/water, show notable improvements in thermal conductivity from 30% to 40%, thereby enhancing heat transfer capability. Nonetheless, their moderate stability and increased viscosity may limit their feasibility for sustained application in engine cooling systems. Carbon-based hybrid nanofluids such as CNT-Al_2O_3/water and graphene-TiO_2/water provide significant enhancements in thermal conductivity, achieving improvements between 40% to 50%, and exhibit excellent heat transfer properties. However, their augmented viscosity and high production expenses restrict their widespread application [14, 51].

Hybrid nanofluids, despite their excellent thermal properties, still encounter practical challenges. For instance, metal-carbon hybrid nanofluids like Cu-CNT/water and Al_2O_3-graphene/water exhibit marked improvements in thermal conductivity (approximately 35% to 45%) and demonstrate remarkable stability with minimal corrosion risk, making them ideal for engine cooling systems. Despite these advantages, nanofluids often face issues such as moderate viscosity hikes and increased production costs compared to metal-metal oxide solutions [25, 53]. In contrast, metal-polymer hybrid nanofluids such as Al_2O_3-PVP/water and CuO-PVP/water generally show moderate enhancements in thermal conductivity, typically between 20% and 30%. These combinations are particularly efficient in providing stability, managing viscosity, and resisting corrosion. Their strong economic feasibility and durability make them particularly appealing for applications where it is essential to sustain cost-effectiveness and long-lasting functionality.

To select appropriate hybrid nanofluids for engine cooling, one must consider both their effectiveness and costs. Hybrid nanofluids incorporating rare-earth elements, such as CeO_2-TiO_2/water and CeO_2-CuO/water, provide a moderate boost in thermal conductivity, ranging from 20% to 30%, and show excellent stability. However, their high price and relatively limited heat transfer efficiency, particularly when contrasted with carbon-based or metal-carbon nanofluids, hinder their extensive application [51]. Thus, achieving a balance between thermal performance and economic feasibility is vital. While nanofluids based on carbon and metal-carbon hybrids offer exceptionally high thermal conductivity, they also increase viscosity, require more pumping power, and reduce flow efficiency, complicating their use in high-performance engine cooling systems. It is essential to develop innovative methods to lower viscosity without compromising thermal characteristics. Moreover, stability challenges pose considerable difficulties, particularly for carbon-based nanofluids that have a tendency to aggregate and settle, which can result in blockages and decrease the effectiveness of cooling systems. While metal-polymer and rare-earth metal nanofluids offer improved stability, corrosion issues continue to be a significant concern for both metal-metal oxide and carbon-based nanofluids, potentially damaging engine components over an extended period [4, 55]. Employing corrosion inhibitors or substituting materials can mitigate these issues, although these measures might increase costs and complicate implementation.

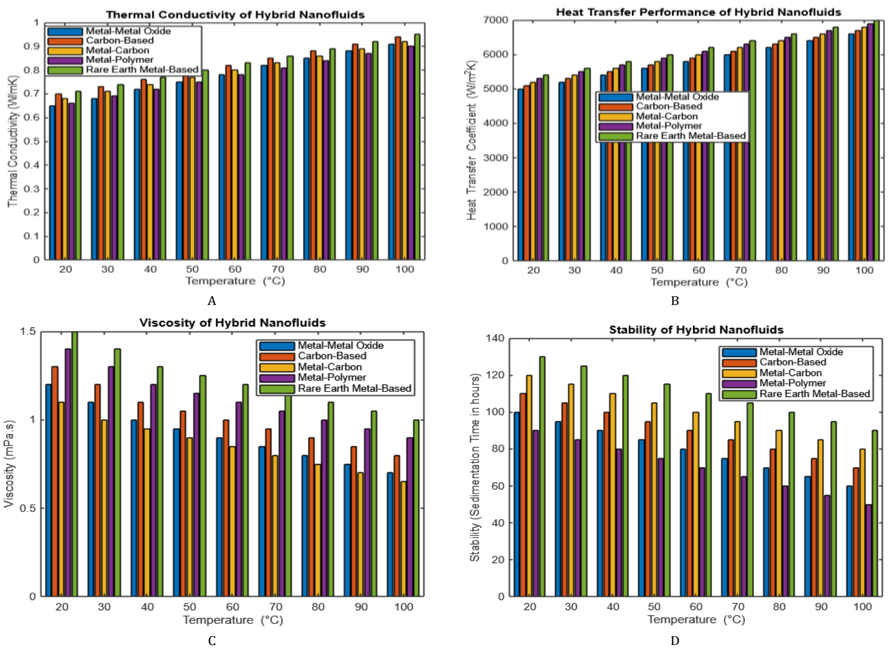

Fig. 4. Hybrid nanofluid performance (original visualization based on [21, 31, 47])

Table 2. Hybrid nanofluid effects [24, 68, 69]

Type	Composition	Thermal conductivity enhancement	Heat transfer performance	Stability	Viscosity increase	Corrosion effects	Cost	Overall rank	Reference
Metal-metal oxide	Cu-Al_2O_3/Water, Cu-TiO_2/Water	✓✓✓ High (30–40%)	✓✓ very good	✓ Moderate	✓ Moderate	✓✓ Low-Moderate	✓✓ Affordable	☆☆☆ (3.5/5)	[24, 32, 49]
Carbon-based	CNT-Al_2O_3/Water, Graphene-TiO_2/Water	✓✓✓ Very High (40–50%)	✓✓✓ Superior	✓✓ Low-Moderate	✗ High	✓✓ Moderate	✗ Expensive	☆☆☆☆ (4/5)	[12, 83]
Metal-carbon	Cu-CNT/Water, Al_2O_3-Graphene/Water	✓✓✓ High (35–45%)	✓✓✓ Excellent	✓✓✓ Excellent	✓ Moderate	✓✓✓ Low	✓✓ Affordable	☆☆☆☆ (4.2/5)	[24, 70, 72]
Metal-polymer	Al_2O_3-PVP/Water, CuO-PVP/Water	✓✓ Moderate (20–30%)	✓ Good	✓✓✓ Excellent	✓✓ Low	✓✓✓ Low	✓✓✓ Cheap	☆☆☆☆ (4/5)	[5, 68]
Rare earth metal-based	CeO_2-TiO_2/Water, CeO_2-CuO/Water	✓✓ Moderate (20–30%)	✓ Good	✓✓✓ Excellent	✓✓ Low	✓✓✓ Very Low	✗ Expensive	☆☆☆ (3.2/5)	[44, 75, 81]

The expense significantly hinders the broad adoption of hybrid nanofluids for engine cooling purposes. As shown in Table 2, although carbon-based and rare-earth metal-based hybrid nanofluids exhibit exceptional thermal properties, their high production costs severely restrict their commercial scalability. Conversely, metal-metal oxide and metal-polymer hybrid nanofluids offer a cheaper alternative. However, their relatively moderate thermal conductivity might restrict their efficiency in demanding cooling scenarios [35, 61]. This highlights the urgent need for innovative, cost-efficient formulations that provide enhanced thermal conductivity while ensuring long-term stability and affordability.

In essence, while hybrid nanofluids present significant potential to enhance the effectiveness of engine cooling systems, their real-world application is hindered by factors such as increased viscosity, difficulties maintaining dispersion stability, corrosion concerns, and substantial costs. Figure 2 illustrates, and Table 2 elaborates, that the deliberate selection and formulation of hybrid nanofluids play a pivotal role in aligning thermal performance with practical application. Upcoming research endeavors should prioritize creating novel hybrid nanofluids that heighten thermal conductivity, improve dispersion stability, and reduce viscosity, all at an economical cost. Achieving this equilibrium is crucial for the broad adoption of hybrid nanofluids in engine cooling, promoting advancements in efficient, long-lasting, and reliable thermal management systems within the automotive sector.

4.3. The effect of hybrid nanofluids with surfactants for engine cooling systems

Integrating surfactants into hybrid nanofluids holds substantial promise for improving their efficiency in engine cooling applications. As illustrated in Fig. 5, surfactants like Sodium Dodecyl Sulfate (SDS) play a crucial role in improving the dispersion and stability of nanoparticles, thereby enhancing both their thermal and fluid dynamic properties [20, 64]. Table 3 compares hybrid nanofluids, distinguishing between those incorporating surfactants and those without, and underscores the notable benefits linked to surfactant usage. Hybrid nanofluids without surfactants generally demonstrate high thermal conductivity; however, they often face issues with particle agglomeration, which diminishes their overall effectiveness [57, 62]. In contrast, the addition of 1% SDS surfactant enhances thermal conductivity by roughly 2–5% due to better nanoparticle dispersion and minimized agglomeration. Although the improvement is moderate, it significantly boosts heat transfer efficiency in engine cooling applications.

One significant advantage of employing surfactants lies in their ability to decrease viscosity, which is crucial for evaluating engine cooling performance. Typically, in the absence of surfactants, hybrid nanofluids present higher viscosity, leading to increased demands for pump power and reduced fluid flow effectiveness. Nevertheless, adding 1% SDS surfactant can reduce viscosity by about 10–15% by promoting particle dispersion and decreasing interparticle friction [63]. A reduction in viscosity translates to lower energy requirements for pumping and enhanced fluid dynamics, leading to more streamlined flow conditions and a pressure drop reduction of about 5–10%, thereby enhancing the cooling system's performance [47].

The addition of surfactants significantly increases the duration of stability in hybrid nanofluids. In the absence of surfactants, these nanofluids are prone to settling over time, potentially leading to blockages and decreased thermal effectiveness. Table 3 shows that incorporating 1% SDS surfactant plays a crucial role in sustaining long-term dispersion stability, thus avoiding particle clustering and settling. Enhancing stability is crucial for engine cooling systems as it ensures reliable and steady performance over extended durations. Moreover, surfactants like SDS can help reduce corrosion by creating protective coatings on metal surfaces, thereby curbing oxidation and extending the life of engine components.

Surfactants provide notable advantages when used in hybrid nanofluids; however, they also introduce some challenges. These agents can lead to extra chemical interactions that might influence the fluid's long-term performance. Therefore, it is crucial to regulate surfactant concentrations carefully, as excessive amounts can cause issues such as

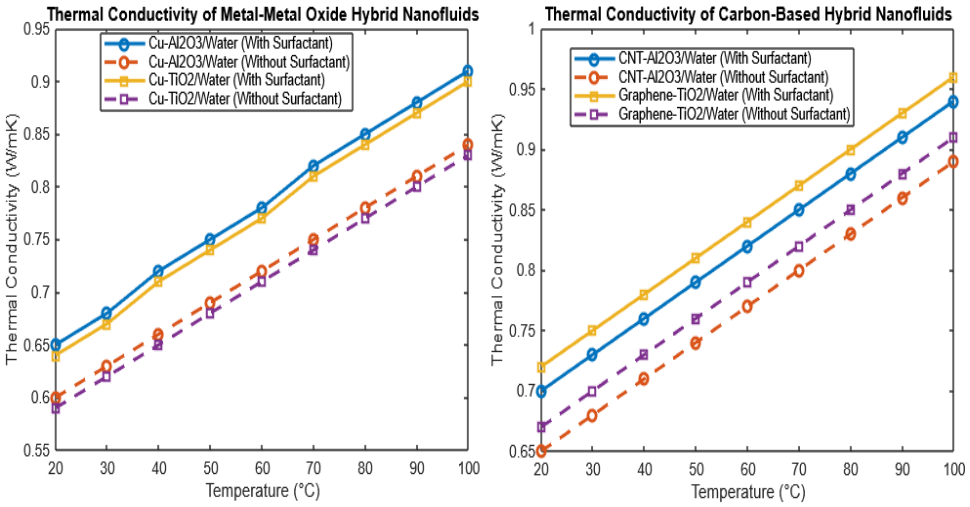

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Fig. 5. The effect of hybrid nanofluids with and without surfactants for engine cooling systems [35, 47, 62]

Table 3. Summery the effect of hybrid nanofluids with and without surfactants for engine cooling systems [38, 48, 68, 71]

Property	Effect without surfactant	Effect with 1% sds surfactant	Reference
Thermal Conductivity	□ High, but particle agglomeration may reduce performance.	□ Slightly improved (~2-5%) due to better dispersion.	[38, 71]
Viscosity	□ High, causing higher pump power consumption.	□ Reduced (~10-15%) due to better particle spacing.	[48, 68]
Stability	□ Moderate risk of sedimentation over time.	□ Highly stable (long-term dispersion).	[54, 59]
Corrosion Risk	□ Low	□ Even lower, as SDS prevents oxidation.	[22, 59]
Pressure Drop	□ Slightly high due to viscosity.	□ Reduced (~5-10%) due to smoother flow.	[24, 69]

foaming. Despite these concerns, surfactants are vital for improving thermal conductivity, lowering viscosity, increasing stability, and reducing corrosion risks, demonstrating their effectiveness in hybrid nanofluids for engine cooling [36, 67].The integration of surfactants into hybrid nanofluids enhances thermal performance, fluid dynamics, and stability, as demonstrated in Figure 5 and Table 3. Surfactants like SDS are vital in addressing the key challenges tied to hybrid nanofluids, enhancing their efficiency in engine cooling applications. Future studies should focus on fine-tuning surfactant concentrations and investigating different surfactant varieties to bolster the performance and reliability of hybrid nanofluids in real-world cooling situations.

4.4. Improvements with surfactant addition in hybrid nanofluids

Hybrid nanofluids, formed by dispersing distinct nanoparticles into a base fluid, provide promising advancements for improving heat transfer in numerous applications, especially in heavy-duty diesel engines. Studies highlighted in [52, 69] involving truck engines demonstrated that CuO-Al_2O_3 hybrid nanofluids could reduce operating temperatures by approximately 7–10°C. The main factor behind this reduction is CuO's superior thermal conductivity, which enables rapid heat release, thereby decreasing fuel consumption and emissions. While this is advantageous, CuO nanoparticles pose a corrosion risk that necessitates the use of anti-corrosion additives, thereby adding to the complexity and expense of maintenance. Moreover, achieving long-term stability presents a challenge; however, surfactants mitigate this by lowering the surface tension between the nanoparticles and the base fluid, promoting even distribution and preserving consistent thermal properties over time. Hence, selecting appropriate nanoparticles and surfactants is critical for maximizing heat transfer efficiency, improving system compatibility, and ensuring ongoing stability [70].

The automotive sector is not just focusing on the applications of heavy-duty engines but is also investigating the use of hybrid nanofluids to improve thermal management in high-performance and electric vehicles. Ensuring ideal thermal conditions is crucial for the lifespan of batteries and the system's overall efficiency in electric vehicles. Studies reveal that hybrid nanofluids effectively reduce battery temperatures, thereby decreasing the risk of thermal runaway and boosting energy efficiency [21, 72]. For high-performance internal combustion engines, improved heat dissipation enhances both efficiency and durability. Car manufacturers are extensively testing hybrid nanofluids; however, their broad adoption is limited due to cost and scalability issues [77, 80]. Currently, the complex and costly processes involved in producing and distributing nanoparticles impede their accessibility in the mass market. Furthermore, challenges related to standardization and regulatory compliance also impede their large-scale commercial application.

An evaluation of the compositions of hybrid nanofluids, as depicted in Fig. 6 and Table 4, highlights the interaction among thermal conductivity, viscosity, stability, corrosion, and cost factors. For example, a mixture consisting of Al_2O_3, SiO_2, TiO_2, and SDS in water showcases both superior stability and controllable viscosity, with a considerable increase in thermal conductivity ranging from 20% to 30%

[77, 81]. SDS is crucial for ensuring stability by preventing particles from clumping together. In contrast, although incorporating MWCNTs with Al_2O_3 boosts thermal conductivity by 35–50%, this combination leads to notable downsides, including extremely high viscosity and insufficient stability due to poor dispersion. Similarly, CuO-based nanofluids provide excellent thermal conductivity but carry a moderate corrosion risk. The cost variability across formulations, notably the higher expense of MWCNT-based fluids, underscores the need for comprehensive design strategies that integrate performance, cost, and reliability, including surfactant use for stability. Although hybrid nanofluids show considerable promise for experimental and practical applications in engine cooling, their widespread adoption is hindered by challenges related to economic feasibility, scalability, and stability [26, 58]. Future research should aim to reduce nanoparticle production costs, enhance stabilization methods, and conduct thorough evaluations of long-term durability. Advancements in nanotechnology, manufacturing processes, and regulatory frameworks can enhance the adoption of hybrid nanofluids for engine cooling, thereby improving efficiency, reducing emissions, and extending engine life [15, 49].

Figure 6c demonstrates the impact of different formulations on viscosity properties, based on experimental findings. The displayed values relate to the dynamic viscosity, an important factor in evaluating water-based nanofluids for use in engine cooling systems. These viscosity changes highlight relative differences under laboratory settings, using the viscosity of water at 25°C as a reference point. It is crucial to note that this study does not take into account the variations in water viscosity across temperatures between 20°C and 80°C. Subsequent research should include these temperature-induced changes to facilitate more precise analyses of viscosity variations with temperature. While the rise in viscosity might seem significant, it is relatively modest when compared to the much higher viscosities of standard engine or transmission oils, which far exceed that of water. Therefore, the findings have been characterized as indicating a "moderate increase in viscosity."

Figure 6 and Table 4 highlight the essential importance of surfactants in enhancing the performance of hybrid nanofluids. Surfactants are essential in improving nanoparticle dispersion and stability, resulting in enhanced thermal conductivity and more efficient heat transfer. Therefore, they are crucial for the optimal performance of hybrid nanofluids in engine cooling systems. Among the evaluated formulations, the Al_2O_3 + SiO_2 + TiO_2 hybrid nanofluid stands out for its well-rounded performance, demonstrating exceptional stability, moderate viscosity, and significant enhancements in thermal conductivity. In contrast, while CuO-based hybrid nanofluids exhibit outstanding heat transfer capabilities, they often have higher viscosity and a tendency to cause corrosion, which might limit their practical applications. These findings emphasize the necessity of careful nanoparticle selection to maximize benefits while minimizing drawbacks.

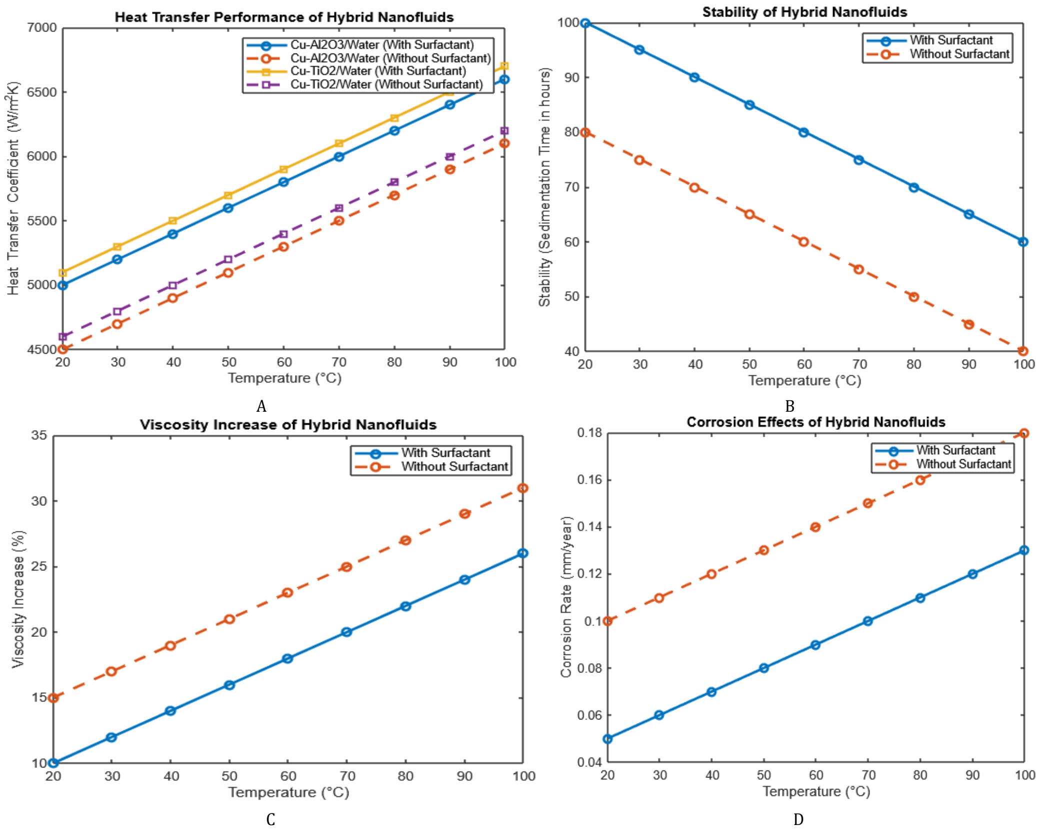

Fig. 6. Viscosity increase (%) of hybrid nanofluids relative to water at 25°C (dynamic viscosity; ASTM D445). Heat transfer coefficient and stability data are derived from [59, 62, 68]. Water's viscosity trend (dotted line) is included for reference (data from [60]). Note: Viscosity values represent percentage change based on literature-reported experimental data. Under general physical principles, viscosity typically decreases with temperature; the values shown reflect formulation-specific behaviors

Table 4. Summary improvements with surfactant addition in hybrid nanofluids

Nanoparticle composition	Base fluid	Fraction [%]	Thermal conductivity [W/m·K]	TC improvement [%]	Viscosity effect	Stability	Corrosion effect	Cost	Overall rank
Al_2O_3 + SiO_2 + TiO_2 + SDS	Water	49.5% Al_2O_3 + 29.7% SiO_2 + 19.8% TiO_2 + 1% SDS	0.7–1.2	~20–30%	⚠ Medium	✅ Excellent	✅ Low	§§	1st 🏆
CuO + Al_2O_3 + TiO_2 + SDS	Water	40% Al_2O_3 + 30% TiO_2 + 29% CuO + 1% SDS	1.2–2.0	~30–40%	✕ High	⚠ Medium	⚠ Medium (CuO may accelerate corrosion)	§§§	2nd 🥈
Al_2O_3 + SiO_2 + CuO + SDS	Water	40% Al_2O_3 + 30% SiO_2 + 29% CuO + 1% SDS	1.0–1.8	~25–35%	⚠ Medium	✅ Good	⚠ Medium	§§	3rd 🥉
MWCNT + Al_2O_3 + SDS	Water	50% MWCNT + 49% Al_2O_3 + 1% SDS	2.0–3.5	~35–50%	✕ Very high (causes flow issues)	✕ Low (difficult to disperse)	⚠ Medium	§§§§§	5th
TiO_2 + SiO_2 + SDS	Water	50% TiO_2 + 49% SiO_2 + 1% SDS	0.6–1.1	~15–25%	✅ Low	✅ Excellent	✅ Low	§	4th

Critical factors for the widespread implementation of hybrid nanofluids in industry include cost-effectiveness, meeting regulatory requirements, and their practicality in real-world settings. Despite being currently cost-effective for certain niche applications, the broader use of high-performance hybrid nanofluids relies on developing synthesis methods that are both affordable and scalable. Assessing the long-term environmental effects of nanoparticle-based coolants is essential to meet the ever-tightening regulatory standards. Despite certain challenges, initial tests by automotive manufacturers, especially in high-performance and electric vehicles, highlight the practical advantages and viability of hybrid nanofluids. These experiments provide vital insights that can guide future development and integration strategies. By tackling both practical and regulatory challenges, hybrid nanofluids hold the potential to greatly enhance advanced thermal management technologies, boost engine efficiency, and support more sustainable automotive solutions.

5. Challenges and future research directions

5.1. Economic feasibility

Although hybrid nanofluids present significant benefits compared to traditional coolants, they still face numerous technical, economic, and practical hurdles. To enhance the adoption of hybrid nanofluids in cooling systems for diesel engines, these challenges need to be addressed. Key issues involve cost-effectiveness, scaling for large applications, and sustained reliability, all of which are vital for moving these advanced coolants from research environments to industrial and commercial use.

The significant cost poses a primary barrier to the extensive commercial use of hybrid nanofluids. The processes required for producing, distributing, and stabilizing nanoparticles involve sophisticated techniques, which render these fluids substantially more expensive than traditional coolants. Moreover, the cost is increased due to the elevated prices of raw materials such as copper oxide (CuO), multi-walled carbon nanotubes (MWCNTs), and graphene-based nanoparticles. Also, using methods like ultrasonication, surfactants, or chemical treatments to ensure stable nanoparticle dispersions further escalates the processing costs. While hybrid nanofluids offer superior thermal efficiency, their high price limits market attractiveness, particularly in cost-sensitive sectors like the commercial automotive industry. Subsequent research should aim to develop cost-effective synthesis strategies and scalable production methods, which maintain high performance levels while minimizing overall expenses.

5.2. Large-scale implementation challenges

The shift of hybrid nanofluids from initial research phases to extensive application in industrial and automotive fields faces considerable challenges. Key concerns include maintaining uniformity in production processes and optimizing supply chain logistics, especially for the large-scale manufacturing and distribution of nanoparticles. Additionally, ensuring compatibility with current cooling systems makes broad adoption difficult, as it is essential to thoroughly assess how hybrid nanofluids interact with cooling system components like radiators, hoses, pumps, and engine materials to avoid potential system damage. Furthermore, the lack of standardized testing methods and industry regulations hinders commercial uptake. To address these implementation hurdles, establishing detailed regulatory frameworks and industry-standard compliance guidelines will be crucial.

5.3. Long-term reliability and stability

To ensure effective practical uses, the long-term reliability and stability of hybrid nanofluids must be preserved. Challenges like sedimentation and phase separation are critical since nanoparticles may settle over time, reducing the efficiency of the coolant. Additionally, nanoparticles such as CuO and Fe_3O_4 can cause corrosion and degradation in cooling system components, thereby shortening their lifespan. It is also vital to assess thermal and chemical stability thoroughly, including tests under various temperature cycles, extensive usage, and potential contaminant exposure. Addressing these issues requires future research to concentrate on advanced stabilizers and surfactants that enhance nanoparticle dispersion and reduce sedimentation. Corrosion-resistant formulas need to be developed and rigorously tested in the field and in collaboration with industry to ensure their durability and suitability for maintenance in practical scenarios.

5.4. Future research directions

Hybrid nanofluids hold great potential for improving cooling in diesel engines, as they offer advancements in thermal conductivity, stability, and heat transfer characteristics. Comparative analyses indicate that hybrid mixes such as Al_2O_3 + SiO_2 + TiO_2 achieve a well-rounded performance, whereas CuO-based hybrids excel in thermal conductivity but also present greater challenges with viscosity and corrosion concerns. Therefore, hybrid nanofluids are acknowledged as innovative solutions for reducing engine temperatures, enhancing fuel economy, and minimizing environmental effects. However, their successful implementation requires addressing substantial challenges related to cost, scalability, and maintaining consistent reliability. Future investigations ought to focus on devising cost-effective production methods, undertaking extensive field research, and formulating regulatory frameworks to support market entry. Technological advancements coupled with targeted research are expected to enable hybrid nanofluids to improve thermal management systems within the automotive and industrial fields, leading to more efficient, durable, and environmentally friendly cooling solutions.

6. Conclusion

Hybrid nanofluids mark a notable advancement in enhancing the thermal performance of diesel engines, providing improved heat transfer, heightened stability, and ideal viscosity compared to both conventional coolants and single-component nanofluids. By meticulously combining different nanoparticles, hybrid mixtures enhance thermal conductivity, addressing issues like nanoparticle sedimentation, excessive viscosity, and material incompatibility. Surfactants are crucial, aiding in nanoparticle dispersion, minimizing agglomeration, and decreasing viscosity for better performance and lasting stability. This review highlights:

- Enhanced heat transfer compared to standard fluids
- Boosted dispersion stability by using nanoparticle combinations and surfactants
- Optimized viscosity reduces pumping demands and energy usage
- Effective corrosion prevention through proper nanoparticle and surfactant selection
- Environmental and fuel efficiency improvements due to effective cooling and minimized emissions
- The critical role of surfactants like Sodium Dodecyl Sulfate (SDS) in improving nanofluid attributes
- The continuous challenges faced in introducing products to the market include manufacturing costs, industry certification, and adherence to regulatory requirements
- Suggested future research focuses on cost reduction, durability tests, and the integration of advanced cooling technologies.

Although there are considerable benefits, challenges regarding economic feasibility, scale of implementation, and reliability remain, demanding more research into nanoparticle synthesis, better dispersion techniques, and rigorous durability testing. Moreover, it is crucial to examine regulatory factors and industrial tactics to transform laboratory accomplishments into viable, marketable innovations. Recent advancements indicate that hybrid nanofluids could significantly transform thermal management in a range of applications, including diesel engines.

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